

CONTRASTING MICROSTRUCTURES OF FAYALITIC OLIVINE IN MATRIX AND CHONDRULES IN THE ALLENDE CV3 CHONDRITE.

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One of the most enigmatic characteristics of the Allende CV3 meteorite is the widespread presence of fayalitic olivine with several distinct occurrences [1-4]. Fayalitic olivine is the dominant component of the dark, fine-grained matrix and also occurs as veins and rims in chondrules, replacing both forsteritic olivine and low-Ca pyroxene. It also occurs as an alteration product of CAIs [5]. The origin of these different types of FeO-rich olivine has been the subject of considerable discussion and several different models have been proposed to explain their textural and compositional characteristics. The most widely favored scenario involves formation in the solar nebula either as condensates from a nebular gas (matrix) or by condensation and reaction with an oxidizing nebular gas for the case of rims and veins associated with forsteritic olivine and enstatite [1-3]. Alternatively, it has also been proposed that the replacement of enstatite by fayalite is a solid state oxidation reaction which occurred within a parent body environment [4]. Most recently [6] have argued that essentially all the fayalitic olivine in Allende may have formed by progressive aqueous alteration of matrix and chondrule silicates, followed by metamorphic dehydration of the product phyllosilicates. This model is based on evidence obtained from petrographic studies of dark inclusions in Allende and other CV chondrites [e.g. 7,8] which indicate that these inclusions may have experienced aqueous alteration and dehydration to different degrees and that these same processes have also affected Allende host as well. In an effort to determine which of these models is correct we have undertaken a detailed microstructural study using TEM of fayalitic olivine from a variety of different occurrences in host Allende and compared them with observations made previously on two dark inclusions in Allende [9].

Matrix olivines. Matrix olivines in Allende range from tabular to equant [10]. Many grains appear to be essentially free of dislocations or other defects. However, a significant number do contain submicron inclusion phases (5 to 40 nm), dominantly Mg-Al chromite and pentlandite, usually as individual, isolated grains, but occasionally associated with each other. The largest spinel inclusions may be faceted, but the pentlandite grains are typically not and neither phase appears to have a crystallographic orientation relationship with the host olivine. In addition, very

thin (3-5 nm), irregularly-shaped poorly graphitized carbon (PGC) crystallites are also found associated with the pentlandite, but rarely with the spinel. cursory examination suggests that voids are present within some of the olivine grains, but HRTEM imaging has shown that these regions actually consist largely of PGC.

Olivine veins. [3,4,11] have previously described veins of FeO-rich olivine cross-cutting forsteritic chondrule olivines. They showed that the veins frequently contain abundant chromite and/or hercynitic spinel, sometimes crystallographically oriented with respect to the olivine. These observations are confirmed in this study. The olivine within the veins is typically in crystallographic continuity with the Mg-rich host olivine, but the vein olivine appears strained and contains abundant closely spaced planar defects on (100), essentially identical to those in matrix olivines in Bali [12]. In some veins the interface between the fayalite and the forsterite host is generally sharp, but highly irregular, sometimes displaying a sawtooth texture in which tooth-shaped regions of fayalitic olivine protrude into the forsterite. In contrast, for many veins, there is no clearly defined interface and locally the planar defects extend into the forsterite for up to 100 nm from the main vein. Some veins also contain numerous voids, up to 200 nm in size, which in some cases are faceted. It is not clear whether these voids are the result of preferential ion milling of an additional inclusion phase. Although most veins appear to consist of single crystals, some veins are clearly polycrystalline in character as described by [11]. The occurrence of chromite appears to be variable. The most common occurrence is as nanometer sized platelets, crystallographically oriented with respect to the olivine. In addition, some fayalitic veins have central zones of coarser-grained, elongate chromites which vary from 100 to 200 nm in width and can sometimes be traced over several microns along the vein.

Olivine replacing pyroxene. Fayalitic olivine replacing low-Ca pyroxene is extremely common in Allende and is typically more advanced around the peripheral regions of chondrules, but advanced alteration is sometimes evident in enstatite phenocrysts in the cores of chondrules. The microstructures of fayalite which has replaced enstatite contrast dramatically with both matrix and vein fayalite. This fayalite typically con-

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sists of crystallographically continuous regions of olivine which can extend for several microns or more and is essentially unstrained and free of defects. The only common microstructures are subgrain boundaries which sometimes occur locally within the olivine. Although most regions of olivine are essentially free of inclusions, nanometer to submicron sized inclusions of relict enstatite and chromite inclusions may be present locally. Two distinct occurrences of chromite are commonly observed. In the first case, myriad, nanometer sized inclusions occur decorating subgrain boundaries within the fayalite. In the second case, they can occur distributed close to or at the interface between the fayalite and enstatite. The chromite crystals are invariably extremely fine-grained, typically <10 nm in size and usually subrounded in shape. There is no evidence of crystallographic orientation relationships between the fayalite host and the chromite. The textures resulting from the replacement of enstatite by fayalite are complex, but several different features are commonly observed. In regions where partial replacement has occurred the enstatite has been replaced by tongues of fayalite which protrude into the enstatite for several microns. These tongues are preferentially oriented parallel to the (100) plane of the enstatite and the interface between the two phases is commonly planar, although ledges a few units cells wide are also common along the interface. Where transformation is advanced, very thin, sometimes acicular relicts of enstatite, highly elongate parallel to (100), occur within the olivine. Remarkably, for most occurrences studied to date there is no rational crystallographic orientation relationship between the two phases.

Discussion. The microstructural characteristics of the distinct occurrences of fayalitic olivine in Allende are remarkably different in a number of respects, most notably their inclusion assemblages. These differences are also reflected in distinct compositional differences, as determined by electron microprobe. For example, matrix olivines with their unique inclusion assemblage dominated by pentlandite, chromite, and poorly-graphitized carbon (PGC), have much higher Ni and S contents than the other occurrences of fayalitic olivine. This assemblage is identical to that found in fayalitic olivine grains in two dark inclusions from Allende [9]. This phase assemblage places considerable constraints on the origin of the matrix olivine grains. Contrary to previous proposals, a high temperature condensation origin can be ruled out by the presence of pentlandite and PGC inclusions. Pentlandite is not stable above 610°C and PGC formation is a thermodynamically irreversible process which is only known to occur by the thermal anneal-

ing of complex hydrocarbon precursors, which only form as a result of low temperature processes. These observations are consistent with an origin by dehydration of a phyllosilicate phase such as serpentine. Indeed the microstructures of the Allende matrix olivines bear a very close resemblance to olivines produced by this mechanism in the unique carbonaceous chondrite Belgica 7904 [12]. A similar origin has been proposed for fayalitic veins in forsteritic olivine and fayalite replacing enstatite [6]. However, the microstructural differences between Allende matrix fayalite and the fayalitic olivine which occurs in veins and replacing enstatite do not appear to be readily reconcilable by such an origin. For the latter case, the remarkable degree of crystallinity of the olivine, absence of voids and the fact that the fayalite invariably consists of continuous regions which extended over several microns are not consistent with formation by dehydration, but by some type of solid state replacement reaction. In addition, the presence of chromite crystals decorating the interface between the fayalite and the enstatite suggest that chromite is produced because Cr and Al in the reacting enstatite are not readily incorporated into the product fayalitic olivine and consequently are precipitated at the transformation interface as chromite. This observation is also inconsistent with a dehydration reaction. With the exception of Mn, Fe and Si, there is little evidence of significant elemental mobility in the reaction. For example, electron microprobe analyses show that the Cr and Al contents of the enstatite and the fayalitic olivine (including the nanometer sized chromite crystals) are essentially identical. This would certainly not be expected if the precursor to the olivine were some type of serpentine, because serpentines found replacing enstatite in CM carbonaceous chondrites [14] typically contain up to 2 or 3 wt% Al_2O_3 . Further studies are in progress to address this question further.

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